LCA Case Studies

Using LCA to Assess Eco-design in the Automotive Sector

Case Study of a Polyolefinic Door Panel

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Abstract

Goal, Scope and Background. The new European legislation concerning End-of-Life Vehicles (ELVs) will allow, in 2015, the landfilling of only 5% of the average vehicle weight, which means that the automotive industry must make a great effort in order to design their products taking into account their recyclability when they become waste. In the present work, LCA is used to assess an existing automotive component, a plastic door panel, and to compare it with a designed-for-recycling prototype panel, based on compatible polyolefins.

Main Features. A 'cradle to grave' LCA is carried out for the panel currently produced and the prototype. The following scenarios are analyzed for plastic waste: landfilling (current practice in Spain), energy recovery in a MSW incinerator or in a cement kiln, and mechanical recycling.

Results and Discussion. The production and use phases together contribute more than 95% in most impact indicators. When the current and prototype products are compared, a decrease in the environmental impact appears for the prototype in the production phase and also at end-of-life if recycling is considered with full substitution of virgin polymers. The overall impact reduction ranges from 18% in the toxicity indicators to 80% in landfill use. Energy recovery in cement kilns appears as a good alternative to recycling in some indicators, such as landfill use or resource depletion. A sensitivity analysis is performed on the quality of recycled plastic, and the results suggest that the benefits of recycling are substantially reduced if full substitution is not achieved.

Conclusion. LCA has been shown to be a very useful tool to validate from an environmental point of view a redesigned automotive component; in addition, it has allowed one to identify not only the benefits from increased recyclability, but also improvements in other life cycle phases which were not previously expected.

Recommendation and Perspective. From this case study several recommendations to the company have been drawn in order to design environmentally friendly components for car interiors, and ecodesign is expected to be introduced in the company procedures.

Glossary: ABS: Acrilonitrile-butadiene-styrene; **ASR:** Automobile shredder residue; **DEHP:** Di(ethylhexyl)phtalate; **ELV:** End-of-life vehicles; **EPDM:** Ethylene propylene diene monomer; **MSW:** Municipal solid waste; **MSWI:** Municipal solid waste incinerator; **NEDC:** New European driving cycle; **PA GF:** Polyamide glass fiber reinforced; **PE:** Polyethylene; **PES:** Polyester; **POM:** Polyoxymethylene; **PP T16:** Polypropylene 16% talc filled; **PUR:** Polyurethane; **PVC:** Polyvinyl chloride; **TPO:** Thermoplastic olefin

Keywords: Automotive components; design for recycling; end-of-life vehicles; energy recovery; landfilling; plastic waste; polyolefins

Introduction

Every year, more than a million vehicles are deregistered in Spain (Ministerio de Medio Ambiente, 2001), posing a potential environmental risk, as it has been recognized recently by the European Commission[1], which declared End-of-Life Vehicles (ELVs) as hazardous waste.

In September 2000, the European Directive on ELVs[2] was approved, establishing the framework for an environmentally sound management of automobiles when they reach the end of their useful life. One of the main targets defined by the Directive is the minimization of landfilling as a treatment option.

It has to be acknowledged, however, that automobiles are among the consumer goods with the highest recycling rate, since the metallic fraction, meaning about 75% of the average vehicle weight (Ministerio de Medio Ambiente, 2001), is already recycled, mainly by the steel industry. On the other hand, the remaining 25%, so-called Automobile Shredder Residue (ASR), consisting of plastics, fibers, glass, paint, etc., is currently landfilled in Spain. Anyway, this situation has to change in the near future, since the Directive will allow in 2006 only 15% landfilling, and 5% in 2015.

One of the main challenges in this context is plastics recycling (Fisch 2003). The share of plastic materials in terms of vehicle weight has steadily increased over the last decades, and it is expected to continue increasing, due to several reasons (Bellmann and Khare 1999, 2000):

- Compared to metals, plastic parts typically exhibit 20 to 30 percent weight reduction, meaning greater fuel economy.
- Plastics offer greater design flexibility; they can be moulded to tight tolerances and complex shapes, with lower tooling costs than for most metal stampings and die castings.

Despite all these benefits and versatility, plastics present a bleak outlook once an automobile reaches the end of its running life, since selective dismantling of parts is economically unattractive, and efficiently processing of more than 20 types of plastic typically presented in ASR is certainly a difficult task (Bellmann and Khare 1999, 2000). Nevertheless, the role of plastics is a key one in attaining the directive targets on recycling, if it is taken into account that they represent, on average, 10% of the vehicle weight and the trend for this figure is to increase.

[1] Comission Decision of 22 January 2001 (2001/119/EC).
[2] Directive 2000/53/EC on end-of-life vehicles.

As a consequence, the automotive industry, and specially the manufacturers of plastic components, face the challenge of anticipating and responding to the ELV Directive, through the design of products that meet the customer demands and are recyclable. However, increasing end-of-life recyclability for a given product must not come at the price of increasing the environmental impact in other life cycle phases. LCA can be used to avoid this problem shifting, assessing the overall performance of design strategies and redesigned products before they are put into practice.

1 Goal

In the present study, the following objectives can be identified:

- Firstly, to assess an existing automotive component, in particular a plastic door panel for the interior of the SEAT Ibiza, in order to find out the subcomponents and life cycle phases contributing most to the overall environmental impact.
- Secondly, to compare the current model with a redesigned version, based on compatible and thus recyclable polyolefin.
- And finally, to assess several end-of-life scenarios for the plastic fraction: landfilling (base case), energy recovery in an MSW incinerator, energy recovery in a cement kiln, and mechanical recycling.

2 Scope

2.1 Product description

The product under study is a panel for the driver door of a 3 door SEAT Ibiza. It is supplied to the car manufacturer by Faurecia, which produces and assembles it in a plant located in Abrera (Barcelona). The product (**Fig. 1**) weighs around 3.8 kg and comprises 3 main subassemblies: the panel itself, which makes up 88% of the overall weight, the handle and the door opener, which together make up the remaining 12%.

As can be seen in **Table 1**, the panel is mainly made up of plastics, among which polypropylene 16% talc filled (PP T16) prevails; other materials present are acrilonitrile-butadiene-styrene (ABS), polyvinyl chloride (PVC), polyoxymethylene (POM), polyester (PES), polyurethane (PUR) and glass fiber reinforced polyamide (PA GF). There are, however, some subcomponents made up of zamak[3] and steel, entailing 3% of the overall weight.

[3] Zamak is a zinc alloy containing aluminum, copper, and magnesium.

Table 1: Material split for the current and prototype panels

Material	Current		Prototype	
	Weight (g)	%	Weight (g)	%
PP T16	2,696	70	3,019	80
ABS	283	7	283	8
PVC	180	5	–	–
POM	203	5	23	1
PES	168	4	-	–
TPO	–	–	168	4
PUR	85	2	43	1
Steel	48	1	48	1
PA	43	1	43	1
Zamak	88	2	88	2
Others	43	1	43	1
Total	3,837	100	3,758	100

Table 2: Differences between subcomponents subject to changes in the prototype panel

Subcomponent		Materials	Weight	
Top roll	Current	PP T16 main structure	430 g	610 g
		PVC foil	180 g	
	Prototype	PP T16 main structure	430 g	598 g
		TPO foil	168 g	
Insert	Current	PP T16 main structure	380 g	590 g
		PES/PUR fabric	210 g	
	Prototype	PP T16 main structure	380 g	572 g
		PP/TPO fabric	192 g	
Speaker grill	Current	POM	180 g	180 g
	Prototype	PP T16	131 g	131 g

The prototype panel is very similar to the one currently produced. Only three subcomponents, as shown in Fig. 1, are affected by the new design. However, these subcomponents represent 35% of the product's overall weight. The differences and implications of the new design can be summarized as follows:

- There is a change in materials and weight of the three subcomponents (**Table 2**), implying differences in the production phase.
- Scraps generated during production of the top roll and insert become completely recyclable, whereas in the current model they have to be landfilled, since the mixture of polymers used is incompatible for recycling.
- Assuming a feasible dismantling operation, the end-of-life recyclability is increased, as the main subcomponents are now built in compatible polyolefins (PP/TPO). On the other hand, the current model can be considered non-recyclable, as polyolefins are welded to PUR, PES and POM.

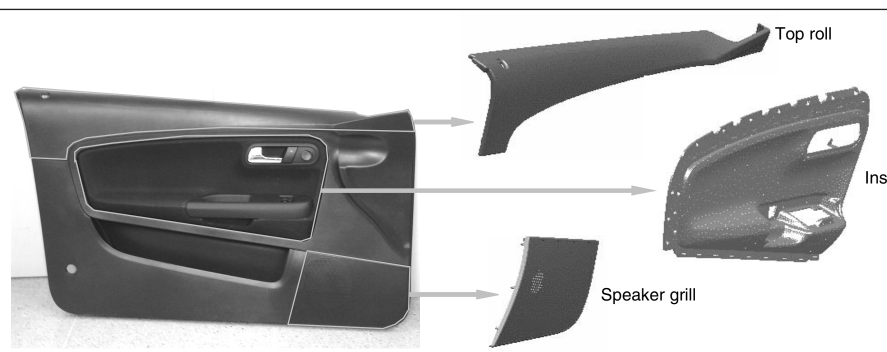


Fig. 1: The product under study and a detail of the subcomponents subject to changes in the prototype

2.2 ELV waste treatment scenarios

Due to the new legislation, the management of ELVs is expected to change significantly in the following years. Although the recycling targets are clear from the directive, there is yet some uncertainty in Spain on the specific means of achieving these targets, and this is specially true for plastic components. For this reason, in the present study, several scenarios have been defined.

For the metallic (ferrous and non-ferrous) fraction of the product, it has been assumed that it is recycled in all scenarios, as this is already the situation in Spain, where these materials are separated after shredding the ELV.

For the plastic fraction, which is by far the most important in the product under study, the following scenarios have been assessed:

- Shredding and landfilling (base case);
- Shredding and energy recovery in an MSW incinerator,
- Shredding and energy recovery in a cement kiln;
- Dismantling of the polyolefinic part of the panel and mechanical recycling; shredding and landfilling of the remaining plastics in the panel.

The recycling scenario has been applied only to the prototype panel, as the current panel is not considered to be suitable for mechanical recycling processes. Landfilling and energy recovery scenarios have been linked only to the current panel, since it has been assumed that the effort of redesigning the prototype does not make sense if it is going to be landfilled or burnt.

It has to be acknowledged that other options for recycling plastic parts from ELVs are being developed, and even LCAs have been carried out for some of them, but due to lack of data they have not been considered in this study. This group of treatment options include, for example, feedstock recycling through the blast furnace (Krinke and Goldman 2003) or by syngas production (Jenseit et al. 2003), and plastic recovery from ASR (François 2003).

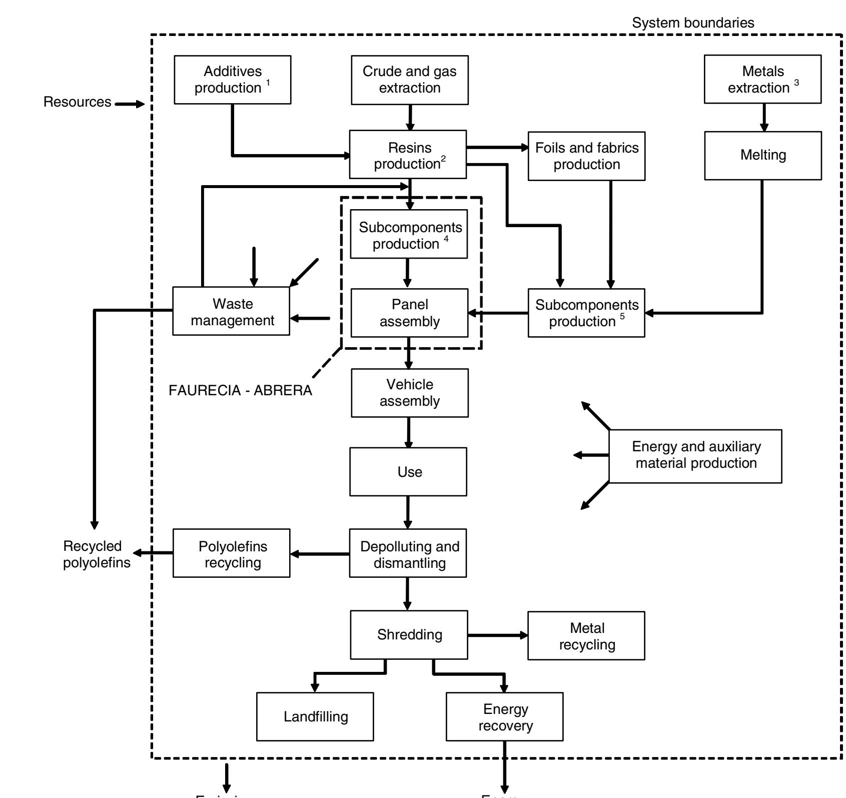
2.3 Function and functional unit

According to the manufacturer (Faurecia 2002), the function of the product can be defined as follows: 'the door panel helps to create a comfortable, ergonomically adapted and high quality environment within the vehicle. It contributes to occupants' comfort by providing ergonomic armrests and controls for the window regulator or mirrors, but also convenient storage space and good acoustic performance through its loudspeakers'. Given that these functional features are equivalent for both the current and prototype panels, a physical functional unit can be chosen. In this case, a single panel has been used as reference flow.

2.4 Product system

The processes included in the product system are displayed in **Fig. 2**. These processes can be summarized as follows:

- Production of materials and processing of these materials to obtain the different subcomponents, including transports between production plants;



[1] Talc, carbon black, DEHP plasticizer, glass fiber
[2] PP, POM, PES, PUR, ABS, PA, TPO, PVC
[3] Iron, zinc
[4] Top roll, insert, carrier
[5] Insert frame, glove box, waist seal, foams, clip holder, speaker grill, grab handle, push housing, push button's housing, front casing, locking control, mirror control, door opener, tweeter, screws

Fig. 2: Product system and system boundaries

- Panel assembly;
- Management of the wastes generated in the previous processes, either by landfilling or recycling;
- Transport of the product and assembly with the rest of the vehicle;
- Distribution of the vehicle to the dealership;
- Use;
- ELV waste management, according to the different scenarios defined in section 3.2, including transport between facilities;
- Production of energy and auxiliary materials consumed in all these processes.

2.5 System boundaries

Three types of boundaries have to be distinguished (Guinée et al. 2002): between the product system and the environment, between included and disregarded processes (cut-off) and between product systems (allocation). In this section, the first two categories are discussed, while allocation rules are detailed in section 3.6.

2.5.1 Boundaries between the economy and the environment

In LCA, all flows should be followed until their inputs and outputs have all been translated into environmental interventions. To create a clear distinction between the product system and the environment, and between elementary and other flows, the system-environment boundary has to be explicitly defined (Guinée et al. 2002).

On top of the system, where resources are extracted and converted to feedstock materials, the boundaries are those considered by the authors of the different databases used. This also applies for energy and auxiliary materials.

In waste management, landfill has been considered within the system, and also wastewater treatment; therefore in those cases where a plant discharges wastewater to the sewer, the subsequent sewage treatment as well as the management of sludge has been included. On the other hand, soil is considered part of the environment, hence substances emitted to soil (for example in wastewater sludge or in incineration ashes recovered for use in road construction) are included as such in the inventory phase.

2.5.2 Cut-off rules

The product under study is a complex one[4]. It comprises subcomponents weighting more than 1 kg and others weighting less than 1 g. In order to avoid disproportionate effort on data collection, weight was used as a criterion for cut-off. It was decided to exclude from the production phase those elements weighing less than 10 g. Using this threshold, 55 elements involving altogether only 2% of the overall weight were excluded. Therefore, 36 elements making up the remaining 98% were included within the system.

Recycling or landfilling of wastes generated during processing of the materials, for example in injection moulding, extrusion, calendaring, cutting, etc., were excluded for single flows not reaching the above mentioned threshold, 10 g.

[4] The parts list provided by the manufacturer consisted of 91 single elements.

Finally, capital equipment has also been excluded from the study, due to the difficulty of collecting this kind of data for such a complex system. In addition, the databases used for unit processes (see section 3.7.) do not include this kind of information.

2.6 Allocation

Several processes in the life cycle have caused allocation problems, namely the use phase and waste treatment.

2.6.1 Use phase

During its useful life, the vehicle causes various environmental impacts, related to washing, maintenance checks and fuel consumption (Schweimer et al. 2000), but only the latter aspect has been allocated to the panel, since there is a direct relationship between fuel consumption and vehicle weight. The allocation method consisted of calculating the additional increase in fuel consumption per km due to a minor increase in weight, which is, according to Volkswagen data (Rohde-Brandenburger and Obernolte 2002): 0.15 l petrol and 0.12 l diesel per 100 kg and 100 km, considering the NEDC. These figures do not take into account extra fuel consumption derived from constructional changes (e.g. gear ratio change, bigger engine), which could lead to doubled values (Jenseit et al. 2003). This marginal approach has been chosen since constructional changes are not justified by changes in small components such as the panel.

2.6.2 Landfill

Plastics are the main materials sent to landfill in the system, during the production phase and the end-of-life. The energy consumed by the landfill has been allocated by mass, and with regard to process emissions, it has been assumed that no biodegradation occurs, and that a certain amount of heavy metals is released in leachate; a difference has been made between PVC and the other plastics, since the former has a higher content of additives (Sundqvist 1997), meaning higher potential emissions.

2.6.3 Cement kiln

Using ASR as an alternative fuel in a cement kiln results in a connection of our product system with the system of cement production . The allocation problem has been prevented by system expansion and subtraction of the avoided burdens (ISO 1998). In this way, the system is given credit for the displacement of a certain amount of the conventional fuel used in the cement kiln, namely coal. The system involves processes up to the combustion of the plastics, and the production and combustion of 4 kg of coal are displaced.

2.6.4 Incineration

The environmental burdens of incineration have been assimilated to those calculated by Kremer et al. (1998) for plastics in MSW. The surplus electricity produced is exported to the grid, creating a new allocation problem that has also been avoided by system expansion. When displacing electricity, there is a problem concerning which technology or technology mix is

used in the system expansion. As the present study is prospective, we have tried to identify the long-term marginal technology for electricity production in Spain, using the 5-step procedure proposed by Weidema et al. (1999) and the prospective studies on electricity by the Spanish Institute for Diversification and Energy Saving (IDAE 2000). As a result, natural gas has been identified as the displaced technology.

2.6.5 Recycling

Recycling occurs in both the production phase and the end-of-life, and plastics are the main materials affected. In addition, as can be seen in Fig. 2, there is recycling in closed loop (production phase) as well as in open loop (production and end-of-life phases). Closed-loop recycling does not represent a problem, since the materials do not cross the system boundaries, but open-loop recycling creates an allocation problem that has been discussed for a long time (Huppes and Schneider 1994, Ekvall and Tillman 1997). The focus in this study has been to allocate open-loop recycling in a coherent manner as compared to energy recovery. As we have seen in sections 3.6.3 and 3.6.4, the system receives a credit for the function (energy) that provides to other product systems. Therefore, if the technosphere is to be modeled in an additive way, the system that receives this function should be charged with the environmental burdens. Consequently, the system that provides recycled material to other systems should also receive credit, and the environmental burdens should be allocated to the system picking up the material. The allocation method used in the study is the so-called disposal-load method (Ekvall and Tillman 1997). In this method, materials entering the system, but later leaving it by means of recycling, are not taken into account. Only when the material is destroyed (landfilled or incinerated) is it allocated to the system. The advantage of this approach is that it promotes recyclable products, but on the other hand gives no incentive to use recycled material. Another weakness of this method is that it assumes full substitution of virgin materials by the recycled ones.

2.7 Data sources and quality

The product system has been modeled using mainly commercial databases, but also literature and field data. In **Table 3** the data sources are summarized for the different subsystems. Data for production of energy, auxiliary materials and feedstock materials have been taken from commercial databases. Transport of raw materials and subcomponents between plants has also been modeled with commercial

Table 3: Summary of data sources

Energy	Fuels, electricity	BUWAL 250 and 300 (Habersatter et al. 1996, Dall'Acqua 1997)
Transport	Truck 16 t and 40 t, train electric and diesel	BUWAL 250 (Habersatter et al. 1996)
Auxiliary materials	Unspecified chemicals (inorganic and organic) for fiber dyeing	Frischknecht et al. 1994
	Ammonia, limestone, NaOH, Activated carbon and cement for MSWI	BUWAL 250 (Habersatter et al. 1996); Activated carbon is assimilated to carbon black (Annema et al. 1992); cement is taken from Vereniging Nederlandse Cementindustrie (PRé4 database 1997)
Feedstock materials	PP, PVC, PET, steel, limestone	BUWAL 250 (Habersatter et al. 1996). Limestone is assimilated to talc filler
	PUR, ABS, PA, glass fiber, zamak	IdeMat 96
	POM	Confidential inventory data supplied by CIT Ekologik
	TPO	Composition supplied by Faurecia: 40% PE, 50% PP, 10% EPDM; inventory data from BUWAL 250 (Habersatter et al. 1996) for PP and PE and IVAM LCA Data 2.0. for EPDM
	DEHP plasticizer, carbon black	IVAM LCA Data 2.0
	Plastics compounding	PricewaterhouseCoopers 2001
Production processes	Injection moulding, panel assembly	Plant data supplied by Faurecia (mass balances and energy consumption)
	Calendaring, Foil extrusion	BUWAL 250 (Habersatter et al. 1996)
	Fiber production (PES, PP)	PricewaterhouseCoopers 2001. Melt spinning assumed as a conventional extrusion process
	PES fiber dyeing	European IPPC Bureau 2003. Average from 8 plants in Europe
	Composite fabric production	Plant data supplied by Autotex (energy and water consumption, waste production and management)
	Zinc electroplating and chrome electroplating	Meijer 1992, RIVM 1992
	Screwing	Kemna 1981
	Zamak die casting	Duin and Kerkhoven 1988. Process assimilated to aluminum extrusion.
Distribution and use	Distribution	Schweimer et al. 2000. Distribution within Spain
	Additional fuel consumption in the vehicle during use	Rohde Brandenburger and Obernolte 2002
	Tailpipe emissions during use (EURO IV)	Seat 2003, Schweimer et al. 2000b, European Environment Agency 2001
Waste management	Plastic recycling	Heijningen 1992; PricewaterhouseCoopers 2001
	ELV shredding	Metso Minerals 2000
	Steel recycling	BUWAL 250 (Habersatter et al. 1996)
	Zamak recycling	Pré4 Database (1997). Weak data
	Cement kiln	Heyde and Kremer 1997, Denis et al. 1997
	Incineration	Kremer et al. 1998
	Bottom ash recycling (road construction)	Emissions of metals to soil (Kremer et al. 1998, Hellweg et al. 2001)
	Fly ash treatment	Plant data from a Spanish company (ECOCAT)
	Fly ash landfilling	Assumed as inert. Only energy consumption from landfill operation. Data from Spanish landfills
	Plastics landfilling	Energy consumption from landfill operation. Data from Spanish landfills. Data on leachate emissions from Pré4 Database (1997). Weak data
	Wastewater treatment	Hospido et al. 2004

databases, although distances have been determined by interviewing most of the suppliers.

Production processes have been analyzed more deeply, and some field data from the panel manufacturer and its suppliers have been collected: Faurecia supplied data from the Abrera plant, concerning the product assembly, and also on injection moulding, which is the predominant moulding process for the plastics present in the panel. Faurecia data have been used for the other suppliers applying injection moulding. Also a yarn manufacturer, Industrias Murtra, and a composite fabric manufacturer, Autotex, were visited and inventory data were obtained.

Distribution of the finished vehicle was modeled using data from the LCA carried out on the Seat Ibiza by Seat/Volkswagen AG. The use phase has been carefully studied, as it is considered critical in automotive products (Schweimer et al. 2000, 2000b, Castro et al. 2003). Fuel consumption is allocated (see section 3.6.1.) and tailpipe emissions are inventoried taking into account the EURO IV limits for regulated pollutants, while non-regulated pollutants are quantified using previous LCA studies by Volkswagen AG and CORINAIR emission factors.

Waste management has also been studied in detail, except for metal recycling, since these processes are constant in both the current and prototype panels. The focus has been put on plastics waste management. An ELV shredding plant was visited in Barcelona and the energy consumption of the process was obtained. Energy recovery by means of MSWI and cement kiln have been modeled using inventory data from specific studies on the issue. Data for the treatment of incineration residues is in accordance with the situation in Spain: fly ash is stabilized with cement and there is a trend on increasing bottom ash recycling in road construction. Plastic recycling data have been derived from literature, although they have been validated by a Spanish company specialized in automotive plastics recycling, Ramon Ortin. Finally, landfilling has been modeled with the PRé4 database, although energy consumption is updated with data from Spanish landfills, collected in previous studies by our research group.

2.8 Life cycle impact assessment

LCIA has been applied using the midpoint approach (Udo de Haes et al. 1999). The following impact categories and flow indicators (EC, WC, LU) have been used:

- Abiotic Resource Depletion (ARD): kg Antimony eq. (van Oers et al. 2002);
- Global Warming Potential (GWP): kg CO_2 eq. (Houghton et al. 1994);
- Acidification Potential (AP): kg SO_2 eq. (Heijungs et al. 1992);
- Human Toxicity Potential (HTP): kg 1,4-dichlorobenzene eq. (Huijbregts 1999);
- Fresh Water Ecotoxicity Potential (FATP): kg 1,4-dichlorobenzene eq. (Huijbregts 1999);
- Eutrophication Potential (EP): kg phosphate eq. (Heijungs et al. 1992);
- Photochemical Ozone Formation Potential (POFP): kg ethene eq. (Hauschild & Wenzel 1998);
- Energy Consumption (EC): indicator measured in MJ primary energy used;
- Water Consumption (WC): indicator measured in liters. Includes all water used in the system;
- Landfill use (LU): indicator measured in kg waste to be landfilled, regardless the type of waste.

3 Results

The results of the study are structured in two parts. First, a contribution analysis is performed for the panel currently produced, which is later compared to the new design, in order to identify potential environmental improvements.

3.1 Contribution analysis for the current panel

3.1.1 Contributions from cradle to gate

The production phase (from the extraction of resources until the product is assembled, including production waste management) is the most complex in the product's life cycle, due to the high number of subcomponents and processes involved, as well as to the logistics associated to the industrial system. For this reason, this phase has been analyzed more deeply in the contribution analysis, from two points of view: the subcomponents and substages.

Fig. 3 shows the environmental profile of the current panel from cradle to gate, displaying the contribution of several subcomponents that make up the product. In order to simplify the graphics, subcomponents having very low contributions in all indicators have been grouped in the 'other subcomponents' category. It can be seen that four elements, which are among the heaviest ones, account for 75%–95% of the overall contributions all together, depending on the indicator. The insert (590 g) is the subcomponent with the highest impact in most indicators: it is responsible for 78% of the water consumed, 65% of the landfilled waste and 30% of the energy consumed. This is related to its complexity in terms of number of materials (PP/PES/PUR) and production processes, specially the PES/PUR fabric manufacture, which is very intensive in terms of water, energy and chemicals. The carrier is responsible for about 20% of the contribution in 8 indicators, and this can be explained by the fact that it is the heaviest subcomponent in the assembly (1,120 g). The top roll (610 g) and the speaker grill (180 g)

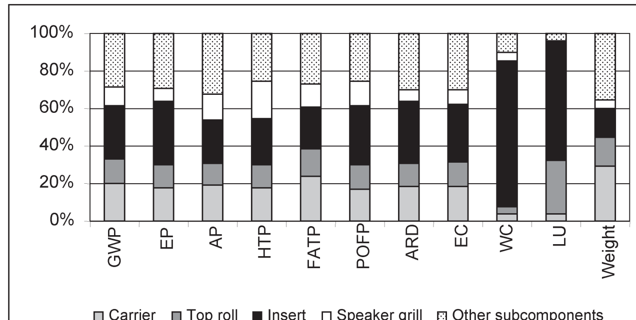


Fig. 3: Contribution of the subcomponents to the environmental profile of the current panel from cradle to gate. The last bar shows the contribution of the subcomponents to the overall weight of the product

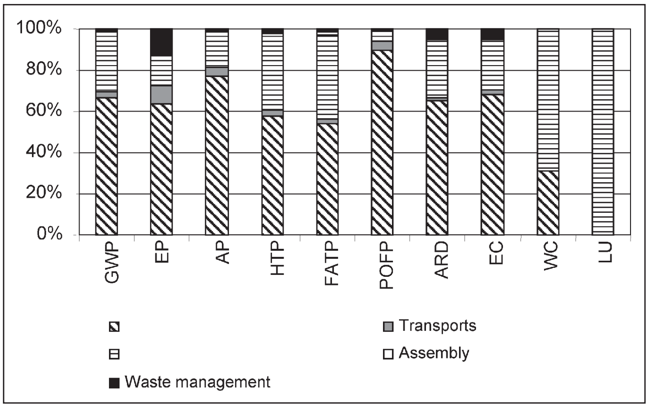


Fig. 4: Contribution of different processes to the environmental profile of the current panel from cradle to gate

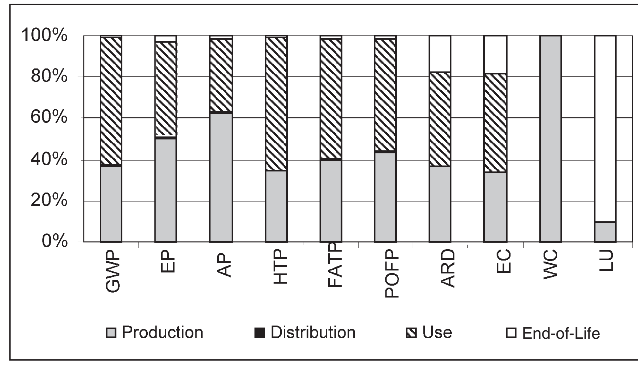


Fig. 5: Contribution of different phases to the environmental profile of the current panel from cradle to grave

have lower but relevant contributions in most indicators: the grill causes 20% of the human toxicity, which is related to the energy intensity of POM production, and the top roll generates 30% of the landfilled waste, due to the multi-material nature of the scraps produced (PP/PVC). Finally, it has to be highlighted that three out of these four elements (insert, top roll and speaker grill) are those affected by design changes in the prototype. Therefore, a wide margin for environmental improvement exists for the new design.

Fig. 4 shows the environmental profile from cradle to gate as well, but in this case the contributions are grouped in five substages of the production phase: production of the raw materials (plastics and metals), production of the subcomponents (moulding of plastics and metals, finishing, etc.), transports (of raw materials and finished subcomponents), assembly (welding of some subcomponents) and waste management (recycling or landfilling of solid waste, and sewage treatment from the production phase). The results show that two substages, namely material production and subcomponent production by injection moulding, represent from 80% to 95% of the overall impacts. On the other hand, transports have a rather low contribution, from 2% to 9%, even when many materials and subcomponents are transported from Central Europe to Barcelona (1,000–2,000 km). Production waste management and assembly are also responsible for a very low contribution.

3.1.2 Contributions from cradle to grave

The overall life cycle for the current panel includes the production phase, distribution, use during 10 years (150,000 km) and, finally, waste management through shredding, recycling of metals and landfilling of plastics. The contribution analysis is displayed in **Fig. 5**.

As can be seen , in 6 out of 10 indicators, the use phase has the highest environmental impact. It is responsible, for example, for a 60% contribution in global warming and in both toxicity indicators. This impact is related to the additional fuel consumption (petrol and diesel oil) in the vehicle, due to the weight of the panel, as compared to the same vehicle without panel. This additional consumption is about 8 liters, assuming 150,000 km traveled during the useful life of the car, according to SEAT data (Schweimer et al. 2000).

The production phase, as discussed in section 4.1.1, is also very relevant in the overall cycle. In fact, it is the most important in water consumption (100%) and in the acidification potential (65%). The high contribution in water consumption is a consequence of the process water used in the production and processing of materials, but also of the absence of water consumption in the use phase, as the inventory data used for petrol and diesel oil do not include this input. In the case of acidification, the lower contribution of the use phase is caused by the low sulphur content of the fuels and by the low NOx emission factors permitted by the EURO IV normative.

On the other hand, distribution has a negligible effect (less than 1% in all indicators) and for end-of-life the contributions are rather moderate, except in landfill use, since all plastics end up in this kind of facility. The environmental credit for metal recycling (not shown in Fig. 5) is negligible, as metals only represent 3% of the overall product's weight.

These results are in line with previous studies, in which the use phase is found to be the most important in the life cycle of automotive components (PricewaterhouseCoopers 2001, Jenseit et al. 2003, Keoleian and Kar 2003). Nevertheless, in the present study, the use phase receives less importance as compared to the other phases, since only the marginal increase in fuel consumption has been allocated to the product, whereas in those previous studies the approach taken is to allocate the average increase, which is higher.

3.2 Comparative assessment of the current and prototype panels

In this section, the environmental impact of the existing and new panels is assessed. In order to identify in which life cycle phase the potential benefits are achieved, the results have been split for production, use and end-of-life. Finally, all phases are aggregated and the overall results are discussed in section 4.2.4.

3.2.1 Production

The environmental impact from cradle to gate of the current panel and the prototype is shown in **Fig. 6**, in which the results of the current panel are expressed as 100% in all indicators.

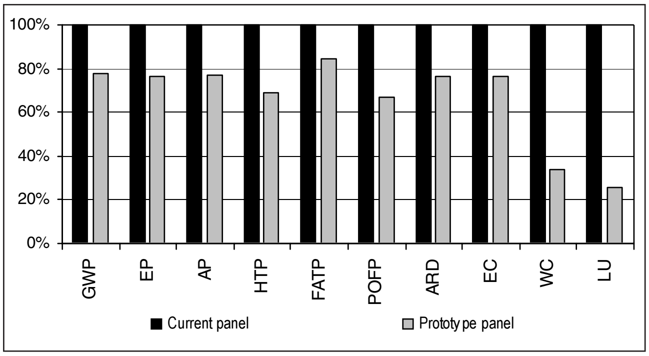


Fig. 6: Environmental impact of the current and prototype panels in the production phase

From the figure, it can be seen that the prototype appears to have a lower environmental impact in all indicators. The decrease ranges from 15% in ecotoxicity to 75% in landfill use and is justified as follows:

- There is a change in materials (PES, PVC, PUR and POM are substituted by PP and TPO) and production processes for three subcomponents. Specially the substitution of PES by PP in the insert's fabric results in the avoidance of the wet dyeing process for PES yarn, as PP yarn is mass dyed. Therefore, a substantial amount of energy, water and chemicals is saved. Also the substitution of POM by PP has to be highlighted, the latter being less energy intensive.
- The process wastes generated by the insert and top roll become completely recyclable in the prototype, implying a raw material saving, as well as a decrease in landfill demand.

3.2.2 Use

As it has been already explained, the environmental impact in the use phase is related to the weight of the product, which implies an additional fuel consumption in the vehicle. However, the weight difference between both panels is very low, being the prototype 2% lighter; as a consequence, the prototype panel is assigned 2% less fuel consumption. Although this saving is not very significant, it is judged as a positive trend, since increasing the weight of the new panel could offset the environmental benefits of the prototype in other life cycle phases.

3.2.3 End-of-life

Four scenarios, as presented in section 3.2., are assessed for the product when it becomes waste. In these scenarios, the metals are recycled, and the plastics are either landfilled, burnt in a MSWI, burnt in a cement kiln, or mechanically recycled, being the last option only possible for the prototype. As can be seen in **Fig. 7**, there are frequently negative values as net results; these arise from the allocation method used, that gives a credit to waste management options providing materials or energy to other product systems.

The landfilling scenario, which corresponds to the present situation in Spain, is not a satisfactory one, since valuable resources are being lost; this option is never very preferable in this set of impact indicators, although several of them demonstrate a better performance than incineration, an option whose impacts are not compensated by the energy recovered, that is assumed to displace electricity from natural gas. On the other hand, recovering energy in a cement kiln obtains better results than conventional incineration. This option displaces the mining and combustion of coal, thus avoiding the leachate emissions of coal storage, and the combustion of this fossil fuel. Furthermore, the ashes of plastics combustion are incorporated in klinker, meaning that zero residues are generated. For these reasons, cement kiln appears to be the best option in ecotoxicity, resource depletion and landfill use. Finally, mechanical recycling obtains the best results in 7 indicators, thanks to the credit given by the virgin polymers displaced (3 kg polyolefins per panel), assuming full substitution between recycled and virgin material. These results are in accordance with those by Jenseit et al. (2003), who identified mechanical recycling as preferable with respect to feedstock recycling (not assessed in the present study), energy recovery and landfilling, but also taking into account full equivalence for virgin and recovered plastics.

3.2.4 Overall results

Finally, the existing panel and the new design have to be compared from cradle to grave, aggregating the previous results for production, use and end-of-life. Distribution is also included, although this phase is constant for both panels.

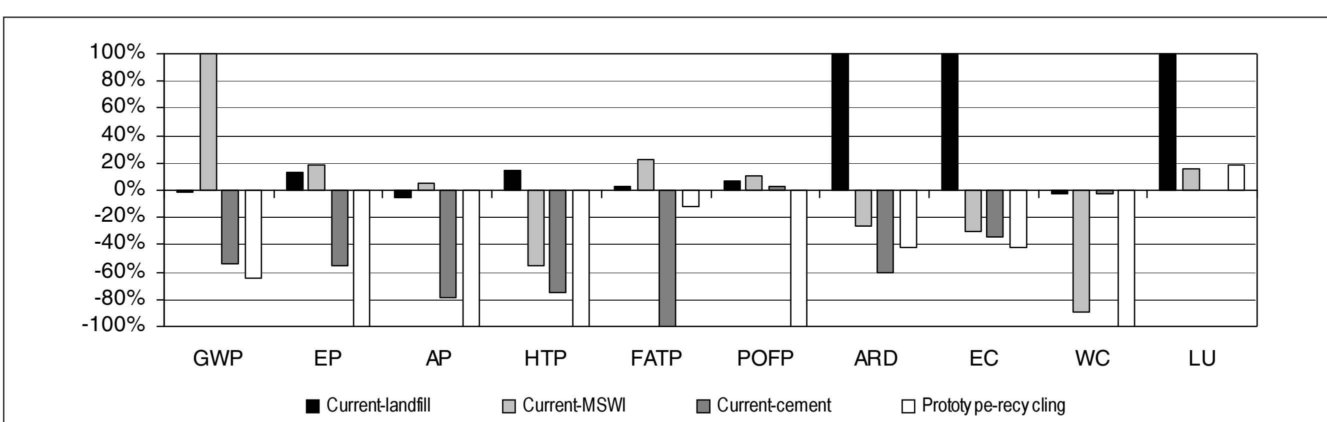


Fig. 7: Environmental impact of the current and prototype panels in the end-of-life phase

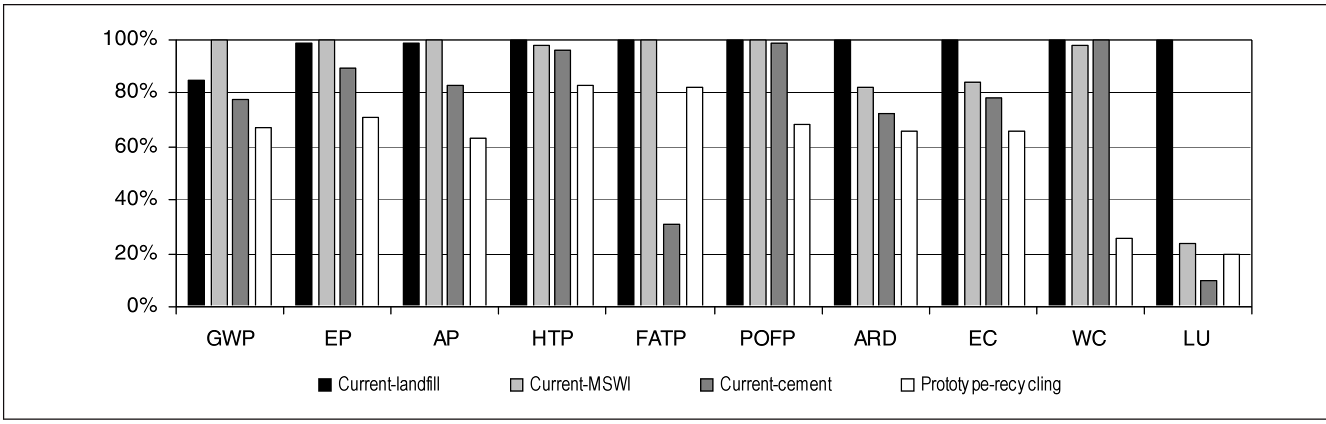


Fig. 8: Environmental impact of the current and prototype panels from cradle to grave

As can be seen in **Fig. 8**, the prototype entails a lower environmental impact in all indicators than the current panel, if the present situation (landfilling) is considered. The impact reduction ranges from 18% in both toxicity indicators to 80% in landfill use. This overall improvement is a consequence of the lower impact caused in the production phase and the credit obtained through recycling of the polyolefins, whereas the use phase remains almost unchanged in both cases. The current panel gets better results than the prototype in ecotoxicity (63% less) and landfill use (50% less), but only in the case of using the plastics as fuel in a cement kiln.

3.3 Sensitivity analysis

The results have shown that recycling the polyolefins from the prototype is the best treatment option in 7 out of 10 impact indicators, due to the credit given to the system thanks to the recycled material. Nevertheless, this judgement is based on the assumption that recovered polyolefins can fully substitute virgin polyolefins (1:1 substitution). However, it is well known that mechanical recycling gives rise to a loss of quality in thermoplastics, derived mainly from breakage and shortening of the macromolecules. As a result, there are some limitations in the applications of recycled plastics, and they can only be used for a limited number of cycles. In this sensitivity analysis the substitution factor for recycled plastics is changed, in order to take into account this limitation.

Substitution factors for recycled plastics are not easy to define, since they depend on the specific material and the intended application. However, some general figures can be found in the literature, such as 1:0.9 (Detzel et al. 2002) and 1:0.8 (Pommer et al. 2003, Hauschild and Wenzel 1998). Another possibility to define a substitution factor is to use the relative economic value of recycled and virgin materials as an indicator of quality loss (Werner and Richter 2000). From the relative prices of PP, the main polyolefin present in the panel, a substitution factor of 1:0.7 can be defined, since recycled PP is about 30% cheaper than the virgin resin (Ortin, 2004). As a worst case, this figure has been used in the sensitivity analysis, and the influence in the end-of-life phase as well as in the overall results has been assessed.

Once the factor is decreased from 1 to 0.7 kg virgin substituted per kg of recycled material, the end-of-life option 'recycling' increases significantly its environmental impact (**Table 4**). With the exception of landfill use, the impact increases from 29% in water consumption to 56% in human toxicity. Hence, it can be concluded that the substitution factor appears to have a strong influence in the end-of-life phase, so that plastic recycling can be no longer be identified so clearly as the most favorable option, with the exception of the indicators of eutrophication, oxidant formation and water consumption. In these conditions, energy recovery in cement kilns can be considered the best option in 7 indicators, and the difference with recycling in eutrophication is very low.

On the other hand, if these modified results are integrated with the rest of the life cycle phases (**Fig. 9**), it can be seen that, in spite of receiving a lower credit by polyolefin recycling, the prototype can still be considered as a better alternative than the existing product, with the same exceptions discussed in section 4.2.4. The main reason is that the benefits of the prototype rely not only on end-of-life recyclability, but also on the improvements achieved in the production phase: change in materials and increased scrap recyclability; consequently, these improvements have to be considered as definitive in the global balance.

Table 4: Results of the end-of-life option 'recycling' taking into account different plastic substitution factors

	GWP (kg CO_2)	AEP kg PO_4^{3-})	AP (kg SO_2)	HTP (kg 1.4 d)	FATP (kg 1.4 d)	POFP (kg C_2H_4)	ARD (Sb kg)	WC (Liters)	EC (MJ)	LU (kg)
Recycling (1:1)	–4.6	–0.0010	–0.045	–0.34	–0.056	–0.0096	–0.024	–7.8	–50	0.71
Recycling (1:0.7)	–2.9	–0.0006	–0.030	–0.15	–0.030	–0.0063	–0.012	–5.5	–25	0.71
% impact increase	36%	41%	33%	56%	47%	35%	51%	29%	50%	0%

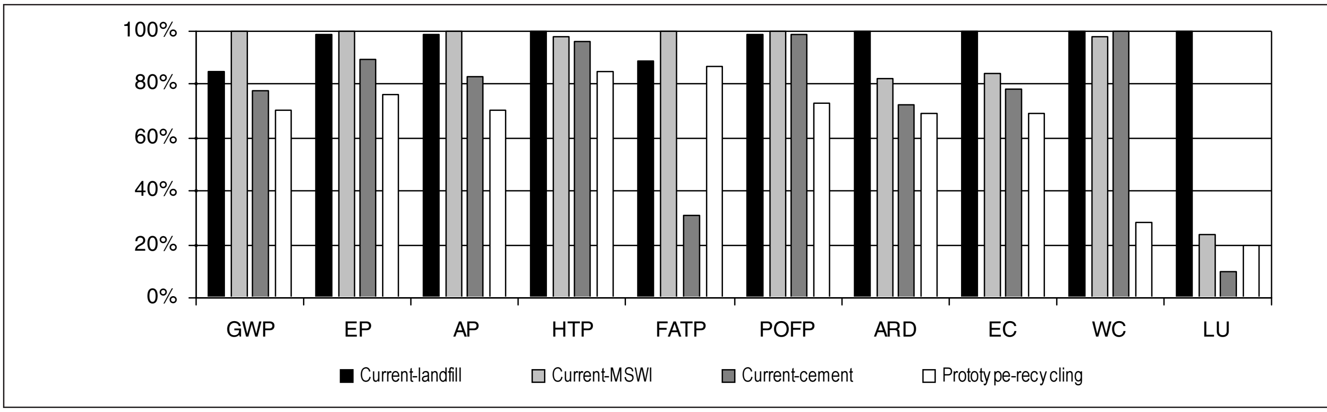


Fig. 9: Environmental impact of the current and prototype panels from cradle to grave, assuming lower quality for recycled plastics (1:0.7 substitution factor instead of 1:1)

4 Conclusions

LCA has been applied to an existing automotive component, i.e. a panel for the driver door of a 3 door SEAT Ibiza, and to a redesigned version of this product which is aimed at complying with the new legislation on ELVs. The main findings from this case study can be summarized as follows:

- Four subcomponents in the existing panel (insert, top roll, speaker grill and carrier) meaning 65% of the product's weight, are responsible for the major contributions (75% to 95%) to the environmental impact of the production phase. Three of these four elements are the ones affected by changes in the prototype.
- The substages contributing most (80% to 95%) in the production phase are material production and material processing (mainly injection moulding and PES/PUR fabric production). Transports of materials and finished subcomponents have a low contribution (2% to 9% cradle to gate).
- The life cycle phases having the greatest environmental impact are the use phase and the production phase. The former is the most important in 6 indicators, due to the increase in fuel consumption registered by the vehicle, associated to the product's weight. The production phase is the most important in the remaining 4 indicators. The distribution phase is negligible and end-of-life, according to the present situation in Spain, is only relevant in landfill use.
- The environmental impact of producing the prototype is reduced with regard to the existing product (15%–75% reduction), thanks to the change in materials and to the increased recyclability of the scraps produced. On the other hand, the impact in the use phase remains almost constant for both panels.
- If full substitution of virgin polyolefins is considered, polyolefin recycling appears as a better end-of-life scenario than energy recovery or landfilling in 7 out of 10 scenarios, but this is strongly influenced by the substitution factor: a factor of 0.7 kg virgin per kg of recycled material significantly increases the impact of recycling, leading to a better relative performance of energy recovery in a cement kiln.
- The global balance of the prototype is favorable with regard to the existing product. Depending on the indicator, the environmental impact decreases between 18% and 80%, respectively, if landfilling and recycling are considered as end-of-life scenarios for the current and prototype panels. This improvement is due first to the changes in the production phase and secondly to increased recyclability. Assuming a lower substitution factor for recycling does not affect this conclusion.
- The assessment of this product implied a series of assumptions, emphasizing the exclusion of certain elements (cut-off), and the allocation methods used in the use phase and in waste management (credits from recovered materials and energy). It is assumed that the uncertainty associated with these assumptions is within the range of current LCA practice, and one of the key issues – virgin plastic substitution – has been subject to a sensitivity analysis. With respect to data quality, the oldest sources only affect minor elements of the panel, being that the majority of the data are from the mid-nineties, and an improvement of the weakest data, which correspond to plastic landfilling, probably would reinforce the conclusions achieved in the study.

Finally, as it has been stated in the introduction, there is some uncertainty on the final treatment that plastics from ELV will undergo in the future, and therefore on whether the new polyolefinic panel will be recycled or not. Also, advanced recycling technologies handling mixed ASR have not been taken into account. Nevertheless, in addition to the benefits from recycling, the application of LCA has allowed one to detect other environmental benefits in the new design, which were not previously expected, namely in the production phase, and that have been found to be essential for a better performance of the new product. In this way, the design-for-recycling process has led not only to a recyclable product, but also to an environmentally improved product through the whole life cycle.

5 Outlook

This work has been carried out during a year, in collaboration with the manufacturer. Although the project began with

Box 1: Ecodesign recommendations for automotive components arising from the case study

1. **Lightweight**. The use phase is critical in automotive components. New designs should never lead to heavier cars, but to lighter ones which can thus achieve a greater fuel economy.
2. **Incorporate recycled materials**. The automotive industry should be responsible not only for providing recycled materials to other industries, but also for using them in those applications where the customer demands can be met.
3. **Incorporate low energy intensity materials**. Materials are the main contributors to the environmental impact in the production phase, and they should therefore be chosen carefully. Energy consumption is a quite simple indicator that can be used for a preliminary screening, if a more sophisticated study such as an LCA cannot be performed.
4. **Simplify**. The results have shown that the more complex a subcomponent is, the more environmental impact it implies, since more materials are used, complexity of the industrial chain also increases, and recyclability is hindered (if ASR recycling technologies are not considered).
5. **Facilitate dismantling**. Selective dismantling of cars is very costly and an arduous task. Automotive components should be designed so that this operation can be carried out as fast as possible.

the new panel model already designed, now the company has realized the usefulness of the tool, not only by the results in this particular product, but also from general ecodesign recommendations that have been drawn (**Box 1**) thanks to the application of the methodology. In short, further research will start with other components, but in this case in parallel to the designing process, in order to take advantage of all the potentials of the LCA tool.

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Economic Allocation in LCA: A Case Study About Aluminium Window Frames

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Abstract. A traditional problem in LCA is how to deal with processes where recycled material is used as an input or where the output of a process is further used as raw material in another product system (open-loop recycling). Allocation is needed to partition the responsibility for the environmental impacts caused by the raw material extraction, the recycling and the final disposal of a material over different product systems in some proportional shares. The norm ISO/DIS 14'041: 1998 now explicitly allows the use of an economic value as a basis for the allocation of open-loop product systems, where material is recycled into other product systems while undergoing a change in its inherent properties.
In a case study for aluminium window frames, an economic allocation procedure for aluminium is developed based on different market prices for secondary materials with different alloy content. Market prices are assumed to reflect the functionality of a material quality within a techno-economic system. Therefore, market prices permit the qualitative description of the degradation of a material over a product system. Based on this qualitative degradation, a 'relative resource consumption' can be defined. This relative resource consumption is used to allocate the environmental impacts related to recycled material entering or leaving the product system under study.
The results of the new allocation principle are compared to results of a former study on window frames out of various materials, elaborated by EMPA in 1996. The conclusions underline the importance of the recycling of aluminium with a high quality and give some criteria for a more ecological design of aluminium windows. Finally, methodological advantages and obstacles of the presented economic allocation procedure are pointed out.

Keywords: Allocation; aluminium; case studies; economic allocation; functionality; LCA; material quality; open-loop recycling; window frames